Characterizing Debris in Circumstellar Environments as Seen by Herschel

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Abstract

We present a debris disk analysis of 350 stars observed by the Herschel Photoconductor Array Camera and Spectrometer (PACS). We target stars with flux measurements at the 70 µm, 100 µm, 160 µm wavelengths that cannot be explained only by a stellar model but can be explained by the sum of a stellar model and one or two debris belts which form a debris disk around the star. Large gaps between debris belts are explained by planets that have formed from circumstellar dust leftover from the formation of the star. Thus, by characterizing debris disks, and depending on the location of the belts in them, we can qualify stars as potentially having planets within their respective habitable zones. We implement two models to recreate the spectral energy distributions (SEDs) of debris disks: the first uses a simplistic black body fit; the second uses a realistic grain model. We find that the realistic grain model improves SED fits compared to a simplistic black body model.
1 Motivation

At night, given preferable viewing conditions, one can step outside and gaze upon countless stars. That word, stars, would be closer examined, however. The solar system, for example, is much more than just a star; the Sun has an entire system of planets, most with their own moons, and two debris belts: an inner, warm asteroid belt, and an outer, icy Kuiper belt. With this in mind, shouldn’t at least some other stars be similar?

All of the dust around the Sun, most of which is located in the asteroid and Kuiper belts, forms a debris disk. In between the Kuiper belt and the asteroid belt there lies the gas giants, and in between the asteroid belt and the sun there lies the terrestrial planets, one of which definitely contains life (hint: it’s Earth). Yet, Earth is a lonely life-bearing planet, and we are ever searching for more planets like ours, parsing through innumerable specks of light throughout the universe.

The motivation of this research project is to characterize each little speck of light in the night sky so that we can model its debris disk. If we can pinpoint the locations of debris belts within a debris disk, then we can identify the regions in which planets would reside; if we know the range of radial locations where planets reside, then we can determine whether a planet lies in the habitable zone—the area where conditions can support biological life as we know it. Technological and resource limitations hinder the discovery and classification of exoplanets, and so the results of this research will narrow the scope of potential star systems with life-bearing planets. We target 350 stars observed by Herschel, only choosing for candidates stars which have excess flux—flux that cannot be explained by a stellar model alone—at longer wavelengths, e.g. 70 µm, 100 µm, and 160 µm.

2 Data Manipulation

For our research, we combined measurements from Herschel Photoconductor Array Camera and Spectrometer (PACS), Spitzer Space Telescope Infrared Spectrograph (Spitzer-IRS), Spitzer Multiband Imaging Photometer (MIPS), Wide-field Infrared Survey Explorer (WISE), and Two Micron All Sky Survey (2MASS). The data are saved in text files, formatted to the standards of the Infrared Processing and Analysis Center (IPAC) at Caltech. Unfortunately, before we could endeavor to do any Spectral Energy Distribution (SED) fitting, we had to fix some of the data in our IPAC tables, and we had to add some missing data to our IPAC tables. All of the data manipulation was done using Python; over 10,000 lines of code have been written in total for the entire project.

WISE

It was discovered that for bright sources, e.g. WISE1 < 8 mag or WISE2 < 7 mag, the most recent AllWISE data is less reliable than the previously measured All-Sky WISE data (WISE ... 2012). Using these criteria, we replaced WISE data for 178 of the 350 target stars.
The *Spitzer* MIPS data was missing from the data tables. We aggregated the missing data from three sources, prioritizing those which are most recent:

2. Chen et al. 2014
3. Berriman et al. 2010

### 2.1 Stitching, Trimming, and Convolving

There were many discontinuities between the 4 *Spitzer*-IRS modules: *Spitzer*-IRS Short Low 2 (SL2), *Spitzer*-IRS Short Low 1 (SL1), *Spitzer*-IRS Long Low 2 (LL2), and *Spitzer*-IRS Long Low 1 (LL1). We used polynomial fits to normalize each module to its adjacent module. We also trimmed any data beyond the 35 µm wavelength. Figure 1a shows the raw data with its discontinuities. Figure 1b shows the stitched and trimmed data, ready to be calibrated to the MIPS 24 µm point by convolving. For *Spitzer*-IRS modules where we did stitching and for which the MIPS data was available, we used the MIPS 24 µm filter response function to calibrate the *Spitzer*-IRS modules to the MIPS 24 µm point. In cases where we did not have MIPS 24 µm data, we did stitching alone, instead relying only on the calibration of SL2. Figure 1c shows the final result of stitching, trimming, and convolving, as well as the raw data for comparison.

![Figure 1](image1.png)

(a) raw data  
(b) stitched and trimmed data  
(c) Stitched, trimmed, and convolved *Spitzer*-IRS spectra for star HD 80950 plotted with the raw data and the MIPS 24 µm point to which the stitched data was convolved.

### 3 Spectral Energy Distribution Fitting

We use two models for SED fitting: a simplistic black body fit and a realistic grain model. In either case, the SED fit is the sum of the flux emitted by the star and the flux emitted by two debris belts. For every star, we run two optimization routines: one fitting a single debris belt, and one fitting two debris belts. We only include observed data points which are less than the saturation limits of each instrument. The best SED fit is chosen using reduced $\chi^2$ values and an $f$ test. Figure 2 shows an SED with just a stellar model fit to the observed data.
3.1 Black Body Fit

We model each simplistic black body debris belt as an infinitesimally thin ring using the Planck function (1). Therefore, the SED model for a two belt simplistic black body fit is the sum of the stellar model multiplied by some normalizing factor and two black belts multiplied each by some respective normalizing factors (2). To optimize the SED model we use a python function from the scipy module: scipy.curve_fit, which uses a linear least squares fitting method to optimize the model to the observed data. The free fitting parameters to optimize are the temperatures of the belts and the normalizing factors for the belts and for the stellar model.

\[ F_\lambda = \pi \cdot B_\lambda(T) = \frac{2hc^2}{\lambda^5}e^{hc/\lambda kT} - 1 \]  

3.2 Realistic Grain Model

A realistic grain model (3) for a single belt calculates the flux contribution from each individual grain. Such a model then depends on the properties of each individual grain in a debris belt, namely the emissivity and the grain temperature. The emissivity of the grain, \( \epsilon \), is obtained using Mie Theory, which needs optical constants obtained from Effective Medium Theory (EMT). We model each grain as having its own temperature, \( T_{\text{dust}}(a,r) \), according to the size of the grain, \( a \), and the distance of the grain from the star, \( r \). A distribution function, \( Ca(r)a^q da \), calculates the number of grains per radial location, which is a gaussian distribution centered at \( r_0 \) with a width of \( 0.10r_0 \), and the number of grains per grain size, which is determined from the slope of steady state collisional cascade, where \( q = -3.5 \) (Morales et al. 2016). The distance of the star from Earth is \( d \). To do a two belt SED fit using a realistic grain model we adopt an optimization function 4, which is also fit using a linear least squares optimization routine as provided by scipy.curve_fit.

\[ F_\lambda = \frac{1}{4\pi d^2} \int_a \int_r \epsilon_\lambda(a) \cdot \pi B_\lambda(T_{\text{dust}}(a,r)) \cdot 4\pi a^2 \cdot Ca(r)a^q da \cdot 2\pi rdr \]  

\[ F_{\text{total}} = N_1 \cdot F_\lambda(r_{0,1}) + N_2 \cdot F_\lambda(r_{0,2}) + N_* \cdot \text{NextGen} \]  

3.2.1 Realistic Grain Properties

We derive the realistic grain properties mathematically using Effective Medium Theory (EMT), Mie Scattering Theory and principles of conservation of energy.

Effective Medium Theory

EMT (5) is used to model an inclusions matrix particle (IMP), which is a mixture of two constituent materials that forms a single grain. One material is the matrix into which the inclusion is embedded. We model grains as having a matrix of dirty
ice, which is composed of water ice, ammonia, and amorphous carbon, and as having astronomical silicate as the inclusions. The optical constants of each grain in the IMP are input as a complex number \( \epsilon = (n + ki)^2 \), where \( n \), the real part, is the refractive index of the grain, and \( k \), the imaginary part, is the extinction coefficient of the grain. The volume fraction ratio, \( f \), is the ratio of matrix to inclusion by volume. We use 0.50 for our IMPs, which is to say our grain is a 1:1 ratio of matrix particle to inclusion particle, by volume. \( \epsilon_m \) is the matrix particle, and \( \epsilon \) is the inclusion particle. \( \epsilon_{av} \) is the resulting inclusions matrix particle. The optical constants of the IMP are then parameters which go into Mie Theory to determine the emissivity of the grain. The optical constants of our IMP are shown in Figure 3a and 3b.

\[
\epsilon_{av} = \epsilon_m \left[ 1 + \frac{3f(\frac{\epsilon - \epsilon_m}{\epsilon + 2\epsilon_m})}{1 - f(\frac{\epsilon - \epsilon_m}{\epsilon + 2\epsilon_m})} \right]
\]  

(5)

Emissivity

We use Mie Scattering Theory to calculate the emissivity properties of the grains. The Mie Theory code was already developed in Python and handed off to us for the project, so there was no interacting with the code beyond inputting the optical constants of the grain and calculating the emissivity of the grain per wavelength of light absorbed into the grain. Through Mie theory, we get an emissivity profile of a grain per wavelength, shown in Figure 4. We find that smaller grains have lower emissivities, while larger grains approach unity emissivity as a simple black body. So, smaller grains will have great impact on the SED fitting procedure as they vary the most in emissivity.
Grain Temperatures

We use the principle of conservation of energy to calculate the temperature of each grain (6). Because we consider mature stars, the grains in the debris disk have achieved thermal equilibrium such that the energy that enters the grain from the star equals the energy that the grain emits. Therefore we can determine the temperatures of the grains by modelling the energy entering the grains as being equal to the energy emitted by the star, for which we know the stellar properties: $R_\star$, the radius of the star; and $T_\star$, the effective temperature of the star.

\[
E_{\text{in}} = E_{\text{out}} \quad \left( \frac{R_\star}{r} \right)^2 \int_\lambda \epsilon_\lambda(a)B_\lambda(T_\star) d\lambda = 4 \int_\lambda \epsilon_\lambda(a)B_\lambda(T_{\text{dust}}(a,r)) d\lambda
\]

(6)

4 Fitting Results

Out of 350 targets stars, our fitting routine successfully optimized simplistic black body parameters for 329 stars. For the realistic grain models, the fitting routine is close to being finished such that we can iterate over all 350 stars, but as of yet we’ve only successfully completed 1 realistic grain model fit. We show the results for star HD 80950, for which we optimized both simplistic black body parameters and realistic grain model parameters.

4.1 Black Body Fits

We ran the fitting module for all 350 stars, yet our fitting procedure only found optimized parameters for 329 stars. 204 stars were best fit with two debris belts, while 125 stars were fit best with a single debris belt. Of those single belt fits, 115 fits were fit best by a single cold belt, while 10 were fit best with a single warm belt.
Figure 5
(a) is a black body fit for source HD 80950. Note that the total flux does not have a steep enough fall off in longer wavelengths to pass through the observed data by Herschel and MIPS. (b) is the distribution of belt temperatures for stars best fit by two debris belts, and (c) is the distribution of belt temperatures for stars best fit by a single debris belt.

4.2 Realistic Grain Model

The realistic grain model for HD 80950 is shown in Figure 6. Although the $\chi^2$ value only improved by 0.2, the total flux for the realistic grain model fits better than the total flux for the simplistic black body fit, because it has a steeper fall off in the longer wavelengths that fits the observed data by Herschel and MIPS better than the black body fit for the same star. This points to ‘$\chi$ by eye’ being necessary to judge the goodness of fit in addition to the reduced $\chi^2$ value.

Figure 6

5 Conclusion and Future Vision

Adopting realistic grain properties allows us to construct a realistic grain model that improves our goodness of fit over that of a simplistic black body fit. Still, the remaining 349 targets need to be modeled using realistic grain properties, and 21 targets need to be redone using the simplistic black body fits. Future work includes utilizing a Markov Chain Monte Carlo optimization routine in lieu of linear least squares optimization. Such a routine enables Bayesian analysis that gives errors on the optimized parameters. We also intend to explore neural networks as a method of optimizing the fitting routines.

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6 References

http://wise2.ipac.caltech.edu/docs/release/allsky/